

## The PSR J0514–4002A binary system in NGC 1851

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**Abstract.** Using the Giant Metrewave Radio Telescope (GMRT), we have discovered PSR J0514–4002A, a binary millisecond pulsar in the globular cluster NGC 1851. This pulsar has a rotational period of 4.99 ms and the most eccentric pulsar orbit yet found:  $e = 0.89$ . The orbital period is 18.8 days, and companion has a minimum mass of  $0.9 M_{\odot}$ ; its nature is presently unclear. After accreting matter from a low-mass stellar companion, this pulsar exchanged it for its more massive present companion. This system presents the strongest evidence to date of such a process.

### 1. Introduction

Since 1987, several globular cluster surveys (see review by F. Camilo and papers by A. Possenti, S. Ransom and J. Hessels, these proceedings) have confirmed that most of the binary millisecond pulsars (MSPs) in globular clusters (GCs) have low-mass white dwarf companions and nearly circular orbits, as observed in the Galactic disk. This is an important confirmation of the evolutionary scenarios proposed by Alpar et al. (1982) for the formation of MSPs.

In GCs, *exchange encounters*, which only have a significant probability of occurring in dense stellar environments, occasionally exchange one of the components of a binary system with a typically more massive star. The exchanges may occur during encounters with either other binaries or with isolated stars. In GCs such encounters can place isolated neutron stars into binaries with a main sequence (MS) star which eventually evolves, “recycles” the neutron star, and finally forms a MSP–WD binary system. Such a process explains the anomalously large numbers of MSPs in GCs (by mass) when compared to the Galaxy.

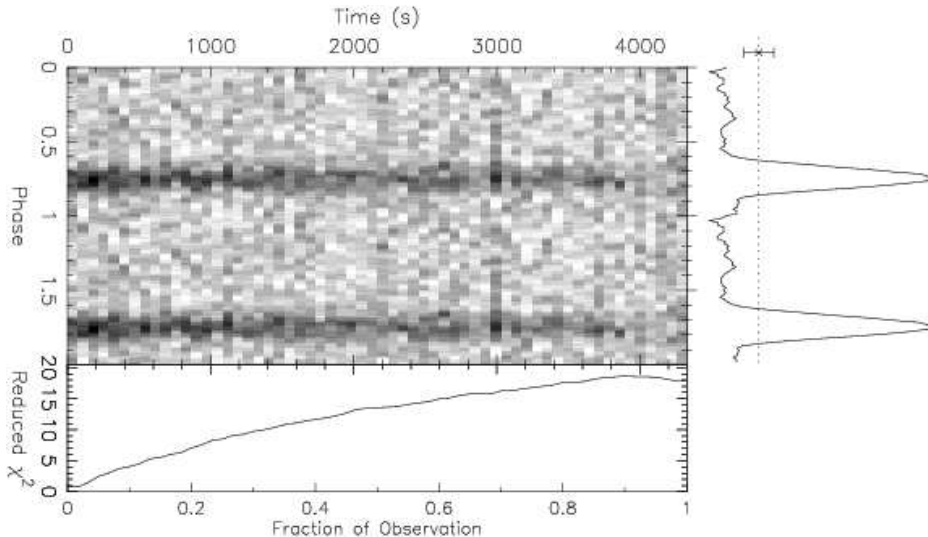


Figure 1. Discovery observation for NGC 1851A, in the globular cluster NGC 1851. Pulsed emission is persistent throughout the whole scan. The pulse profile is rather narrow (right), corresponding to the time resolution of the system for this DM.

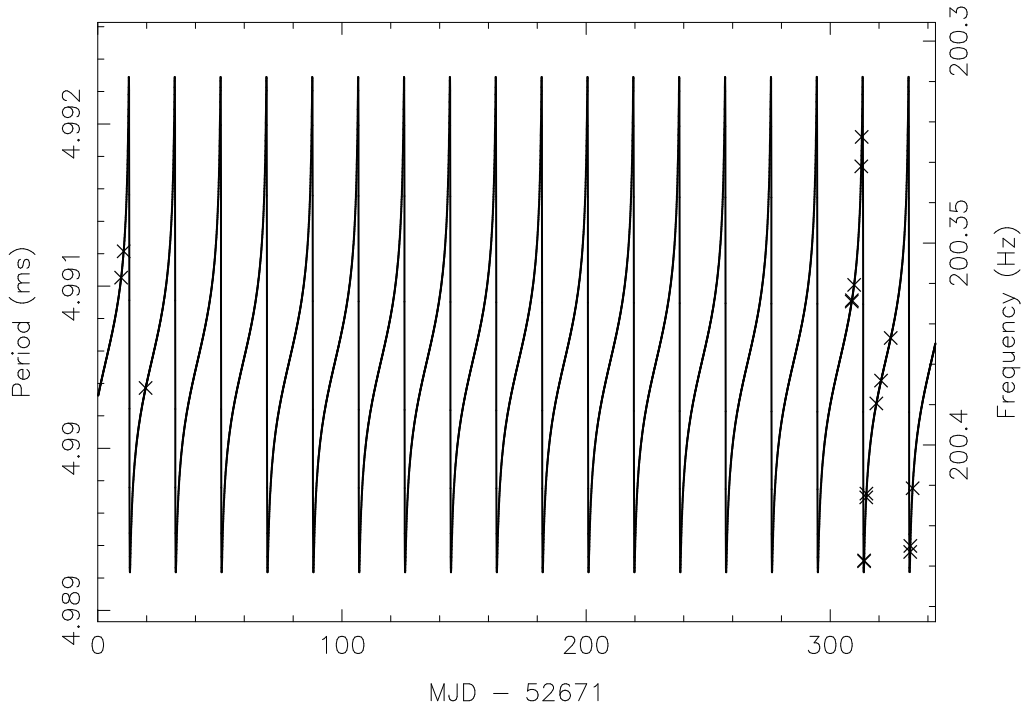
If the companion to the low-mass MS star is a previously recycled neutron star, we observe “irregular” eclipsing binary pulsars (see review by P. Freire).

In this paper we present some preliminary results on a new, unique binary millisecond pulsar, PSR J0514–4002A (henceforth NGC 1851A) in the globular cluster NGC 1851. This has been found in a new, sensitive 327-MHz survey of globular clusters carried out using the Giant Metrewave Radio Telescope (GMRT), at Khodad near Pune, India.

## 2. The GMRT 327-MHz survey and the discovery of NGC1851A

Our use of a low radio frequency for the present pulsar survey is to be contrasted with most recent pulsar surveys, which are carried at higher radio frequencies. This survey is aimed at faint pulsars with steep spectra, which are unlikely to be detectable in a high-frequency survey. This particular survey benefits from the large gain of the central array of the GMRT, 4.6 K/Jy when used in the phased array mode of the Array Combiner (Gupta et al. 2000, Prabu 1997). This produces a beam on the sky with a diameter of about 3 arcminutes. The number of spectral channels across the available 16-MHz band is 256. The sampling time used is  $258 \mu\text{s}$ , each observation consisting of a pair of 72-minute scans containing  $2^{24}$  samples. After this time, the 14-antenna central array is re-phased using a reference source.

We observed a set of 16 GCs in February 2003. The data were written to tape at the GMRT and taken to McGill University, where they were processed using the BORG (a 104-node Beowulf cluster available there for pulsar processing) running the PRESTO software package (Ransom 2001). One of



Figure

2. The measured barycentric rotational periods of NGC 1851A as a function of MJD.

the GCs observed was NGC 1851. Its distance ( $D$ ) from the Sun is about 12.6 kpc (Cassisi, De Santis, & Piersimoni 2001), and its Galactic coordinates are  $l = 244.51^\circ$ ,  $b = -35.04^\circ$  (Harris 1996)<sup>1</sup>. It is a relatively bright globular cluster ( $M_v = -8.33$ ) with a very condensed core ( $c = \log(r_t/r_c) = 2.32$ , where  $r_t$  and  $r_c$  are the tidal and core radii). It is among the ten clusters in the Galaxy with the highest central luminosity density ( $\rho_0 \simeq 2 \times 10^5 L_\odot \text{pc}^{-3}$ ).

In the first scan for NGC 1851, taken on the 10 of February 2003, we detected a clear pulsed signal with a period of 4.991 ms (see Figure 1) and a DM of  $52.15(10) \text{ cm}^{-3} \text{ pc}$ . Analysis of the rotational periods using TEMPO<sup>2</sup> proved most surprising: the best-fit model (see Figure 2) indicates  $e = 0.889(2)$ , the most eccentric orbit of any known binary pulsar and many orders of magnitude more eccentric than the typical MSP orbit (for this and following quantities, the number in parenthesis indicates the  $1 - \sigma$  uncertainty, which we conservatively estimate to be ten times the formal value computed by TEMPO, as there is still no phase-coherent timing solution for this pulsar). The orbital period  $P_b$  is 18.7850(8) days, and the semi-major axis of the orbit projected along the line-of-sight ( $x$ ) is 36.4(2) light seconds. This implies a minimum companion mass

<sup>1</sup>See <http://physwww.physics.mcmaster.ca/~harris/mwgc.dat> for an updated version of the table of globular cluster parameters presented in this paper

<sup>2</sup><http://pulsar.princeton.edu/tempo>

of  $0.9 M_{\odot}$ , assuming a pulsar mass of  $1.35 M_{\odot}$  (for the median of expected inclinations,  $60^{\circ}$ , the companion mass is  $1.1 M_{\odot}$ ). The epoch of periastron  $T_0$  is  $\text{MJD} = 52984.46(2)$ , the longitude of periastron  $\omega$  is  $82(1)^{\circ}$  and the rotational period  $P$  is  $4.990576(5)$  ms. Imaging with the GMRT, made during the search and confirmation observations, has shown that the pulsar is located very near the centre of the cluster (see Figure 3), just outside the 0.06-arcminute core. The estimated flux density at 327 MHz is about  $3.4 \pm 0.4$  mJy.

### 3. Formation and nature

All known eccentric ( $e > 0.1$ ) binary pulsars in the disk of the Galaxy have relatively massive companions. This varied set of companions includes blue giants, other neutron stars and heavy WDs. Blue giants live only a few Myr which is probably not long enough to allow the sustained mass accretion required to spin up a pulsar companion to millisecond spin periods. This is in accordance with the observations, where the pulsars with massive companions have rotational periods of tens or hundreds of milliseconds. In addition, the second supernova event, where the giant becomes a massive compact object, is likely to make the orbit significantly eccentric, presuming the binary survives. Since both stars are now compact, tidal circularization is henceforth impossible. The prolonged episode of stable mass accretion needed to spin up a neutron star to millisecond periods is only possible from evolved lower-mass MS stars. Such large timescales allow effective tidal orbit circularization as well. This process likely created the MSP currently in NGC 1851A, although with a presently unknown low-mass WD companion.

Some MSP + low-mass white dwarf systems found in GCs, like PSR B1802–07 ( $P = 23.1$  ms,  $P_b = 2.62$  days,  $e = 0.212$ , D’Amico et al. 1993) can become mildly eccentric due to interactions with other objects in the cluster (Rasio and Heggie, 1995). This is almost certainly not the origin of the present NGC 1851A binary system since its eccentricity is probably too high to be explained by this mechanism. We are therefore lead to the conclusion that after recycling, NGC 1851A exchanged its former low-mass companion with a more massive object. This is the first system presenting clear evidence of such a process. A massive star (the pulsar’s present companion) passed within a distance smaller than about four times the separation of the components of the previous binary system, a not uncommon event in the dense environment of a GC. The most likely outcome from such an event is the formation of a slightly tighter eccentric binary system containing the two more massive objects (Hut 1996).

The companion of NGC 1851A has a minimum mass of  $0.9 M_{\odot}$  and its nature is as yet unclear, it could be either a compact or extended object. In NGC 1851, a cluster with an age of  $\sim 9$  Gyr (Salaris & Weiss 2002) where  $1-M_{\odot}$  stars are now leaving the main sequence, such objects should be readily detectable by the HST. Because of the lengthy episode of MSP recycling that preceded its formation, the present NGC 1851A binary system is very likely to be a few Gyr younger than the cluster in which it lies. Mathieu, Meibom and Dolan (2004) have determined that, for the open cluster NGC 188 (with an age of 7 Gyr and a stellar population similar to that of GCs), binary systems containing MS stars with orbital periods larger than 15 days have not yet had time to

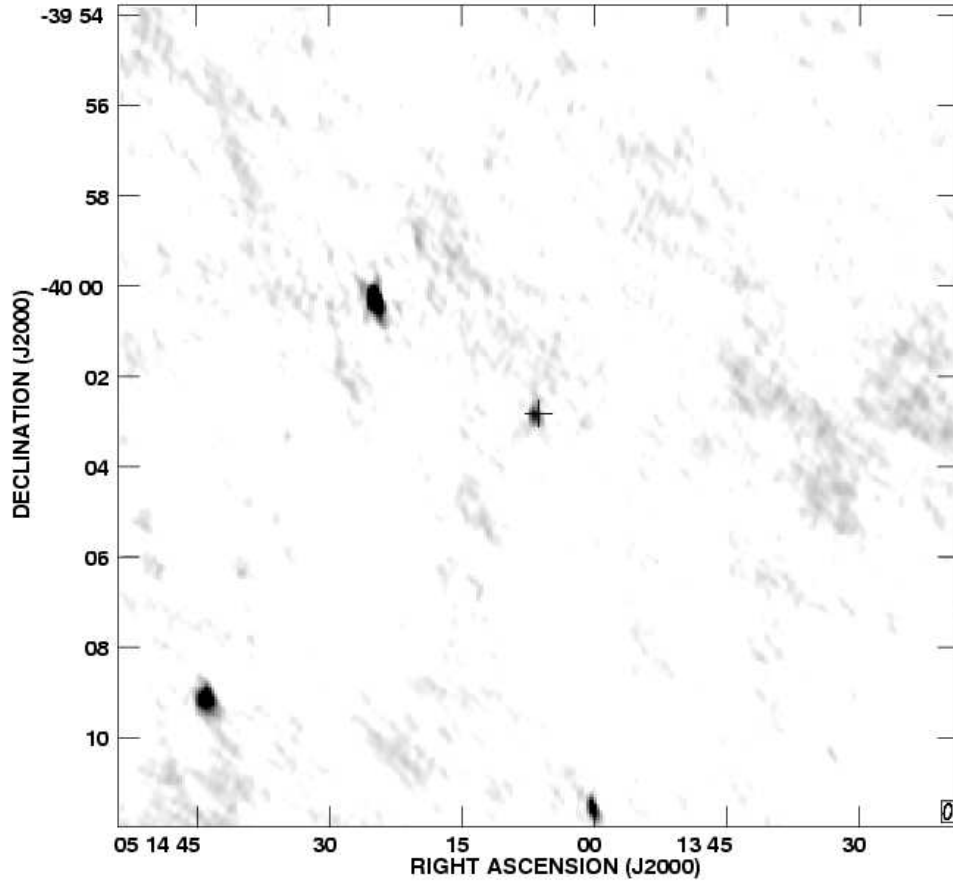


Figure 3. A radio image of NGC 1851 at 327 MHz, made by combining the data from 4 different epochs of observations in December 2003. The pulsar is the faint source near the center of the cluster (indicated by the cross). The brighter source to the north-east is not the pulsar, when the interferometer was pointed at it no pulsed emission was detected. The small ellipse in the lower right corner indicates the dimensions of the synthesized interferometer beam, this interferometer includes *all* the antennas in the array (the pulsation survey used only the central square, which produces a 3-arcminute beam).

circularize. Therefore, the observed eccentricity of the NGC 1851A system does not rule out the possibility of the companion being an extended object. In fact, partial and/or irregular “eclipses” from an extended object such as a MS star may explain the apparent flux variability from NGC 1851A.

#### 4. Conclusion

We have discovered a remarkable 5-ms binary pulsar, the first to be found in the GC NGC 1851 and the first pulsar to be discovered with the GMRT. Its orbit is the most eccentric known for any system containing a pulsar, while its rotational period is much shorter than that of any other pulsar in an eccentric binary system. This combination of characteristics indicates that, after becoming an MSP by accreting matter from a low-mass companion star, this neutron star has almost certainly exchanged it for its present, significantly more massive companion. This is the most effective way of forming a binary system containing a millisecond pulsar and a black hole, provided black holes exist in GCs. Follow-up studies of this object will allow us to determine the nature of the companion and hopefully measure the masses of both components of this binary system.

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